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Modelling Fracture Mechanics: From J-Integral to Phase Field and Innovative Machine Learning Techniques

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This work explores the evolution of fracture simulation methods, starting from the classical J-integral approach and advancing toward modern techniques based on phase-field formulation and deep neural networks. The traditional model relies on explicitly meshing the crack, providing a solid theoretical foundation but often suffering from high computational costs and limitations in handling complex geometries. In contrast, the phase-field method treats cracks as diffused interfaces, eliminating the need for explicit meshing and enabling a more robust simulation of crack nucleation and propagation.
Recent advances in artificial intelligence have further revolutionized fracture mechanics modelling. Deep learning techniques, particularly those employing the Deep Energy Method, integrate the governing differential equations directly into the neural network training process. By defining the loss function in terms of the total system energy, these Physics-Informed Neural Networks (PINNs) efficiently approximate solutions to complex fracture problems while striking a balance between accuracy and computational efficiency.
Two simple case studies are considered to test the performance of the methods. Considering the traditional J-integral as a benchmark, phase field and Neural Network methods are compared. The results obtained with the phase field method align well with the traditional method, showing a significant advantage in the mesh creation. The neural network approach requires initial tuning of the model parameters. In this stage, the number of hidden layers, the number of neurons per layer, the activation function, and the type and number of optimizers must be found to optimize the solution, which must be compared to a reference obtained experimentally or numerically with a traditional model. After that, the model can be run in a few minutes in other loading conditions, leveraging GPU parallel computing. Small changes in the geometry do not require a re-parametrization, but the accuracy of the results is affected. On the other hand, if the geometry and loading condition change significantly, a new parameter set must be found.

Autori principali: Dr. TONCELLI, Martina (Politecnico di Torino); Dr. PISTORIO, Francesca (Politecnico di Torino); CLERICI, Davide (politecnico di torino); Prof. SOMÀ, Aurelio (Politecnico di Torino)

Relatore: CLERICI, Davide (politecnico di torino)

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